OUT OF PLANE IMPACT ON WOVEN COMPOSITES PLATES: EFFECTS OF THICKNESS, PLY SEQUENCE AND PLY CLUSTERING.

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Abstract

The present work aims to reveal the influence of the material structure (number of plies, ply sequence and ply clustering) in woven (AGP 280-5H) coupon response under low velocity impact. To this end a complete set of experiments was design using the ASTM D7136 standards. To analyze the influence of the parameters, the Composite Structure Impact Performance Assessment Program (CSIPAP) proposed by Feraboli and Kedward et al. in 2006 has been used, including on the study the actual monitoring capabilities to address the problem; maximum force, residual stiffness and damages observed are studied.

The study conclude that the maximum force raises with the plate thickness, but the residual stiffness is linear with the ratio between the impact energy and the thickness. Regarding the ply sequence and the ply clustering the orientation and clustering affects to the damage development and thus the residual stiffness varies.

1. Introduction

The application of fiber reinforced plastics in different industries is increasing. The remarkably specific mechanical properties of these materials make them suitable to reduce the weight of the structures. These improvements have a clear economic benefit and make possible to reduce the carbon footprint on transport industries. In exchange the industries need to understand the limits of the materials in all type of loading conditions. Usually this goal is achieved using the test pyramid, understanding the behavior of small coupons to extrapolate conclusions to real structures. Thus understanding and bringing new and extended experimental data to the scientific community is a requirement to spread its usage.

The behavior in the elastic regime in those materials is commonly fully characterized but the non-elastic or damage regime needs to be addressed. Moreover the complexity of the damages observed in laminate materials and its dependence on the loading condition and material configuration increase the number of tests. One of the mayor threats for FRP is the out-of-plane loading conditions such as impacts, which produce interlaminar failures, among others, decreasing drastically the material's strengths in plane. During the last decades, impacts have been one of the most common topics for researchers, who use drop tower or pneumatic launcher in order to reach different impact velocities. The effort in tape laminates was focused in different aspect such as target geometry, impact energy, ply sequence...[1, 2], the studies in woven were focused in the damage produced as a function of energy or varying different parameters of the impact condition [3, 4]. The present work aims to reveal the influence of the material structure (number of plies, ply sequence and ply clustering) in woven coupon response under impact. To this

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end a complete set of experiments was design using the actual ASTM standards, including the actual monitoring capabilities to address this problem.

2. Experimental setup

The experimental campaign presented in this work was design in order to study the influence of thickness, ply sequence and ply clustering in woven laminates under dynamic out-of-plane loading. To this end composite coupons of AGP 280-5H carbon/epoxy satin woven of 150 × 100 mm were manufactured using autoclave methods. Different configurations of thickness (conf. A, B and C), ply sequences (C and D) and ply clustering (E, F and G) were selected as can be observed in Table 1. The coupons were subjected to impacts using the guides proposed in the ASTM-D7136 standard [5] in a wide range of impact energies.

Table 1. Coupons configurations of AGP 280-5H carbon/Epoxy satin woven employed in the study.

Configuration	Thickness [mm]	Number of plies	Ply sequence
A	2.3	8	$(0/90)_{4s}$
B	3.5	12	$(0/90)_{6s}$
C	4.6	16	$(0/90)_{8s}$
D	4.6	16	$(\pm 45)_{8s}$
E	4.6	16	$[(\pm 45)/(0/90)]_{4s}$
F	4.6	16	$[(\pm 45)_2/(0/90)_2]_{2s}$
G	4.6	16	$[(\pm 45)_4/(0/90)_4]_s$

Low velocity impact tests were performed by means of an INSTRON-CEAST 9350 drop weight tower. The instrumented hemispherical striker of 16 *mm* diameter was free fall accelerated through a guide, impacting orthogonally in the center of the coupon [5], registering the force during the impact. The anti-rebound system avoids undesirable multi hits after the impact. The impact energy was obtained only varying the height of the impactor, the striker mass (5.585 *kg*) was maintained unchanged during the tests. In order to evaluate the plate behavior and crack propagation during the impact, tests were recorded using a high speed video-camera (Photron SA-Z 2100K), configured at 20000 fps and with resolution of 1024×1024 pixels, using a mirror placed under the specimen with an inclination of 45^o [4].

To analyze the influence of the plate thickness, ply sequence and ply clustering and completely characterize the impact performance of composite plates under low velocity impacts, the Composite Structure Impact Performance Assessment Program (CSIPAP) proposed by Feraboli and Kedward [6] has been used. This methodology establishes that the peak force, absorbed energy, coefficient of restitution ($COR = \sqrt{(E_i - E_{abs})/E_i}$), contact duration and residual stiffness ($\hat{K}_{D0} = (t_{after}/t_{before})^2$) plots constitute the key information to assets a completely analysis [4].

Once impacted, composite laminates were subjected to a non-destructive damage analysis. The damaged area was evaluated in each coupon by ultrasonic inspections (C-Scan and B-Scan techniques), studying the dispersion and location of the damage inside the composite laminates. Finally, the residual stiffness of the laminates was obtained by comparing the contact time between the specimen and the striker in a sub-critical impact before and after the damage inducing impact. In addition, CAI experiments were carried out using the specifications of ASTM standard [5]. All the experimental test and non-destructive analysis were performed in the University Carlos III of Madrid lab.

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3. Impact test analysis

From the instrumented striker of the drop tower, the force vs time curves were directly obtained. The curves are not filtered according to the ASTM standard test [5]. Fig. 1 shows an example of the results obtained, the curves depicted represent the 3 impact procedure that has been done in the present experimental campaign for each specimen. The laminate was subjected to a sub-critical impact of 3 J followed by the induced damage impact, in this case 15 J, finally a third sub-critical impact of 3 J has been done. The sub-critical impact of 3 J has been chosen because this impact energy is below the delamination threshold; determined for these specimens by a combination of: ultrasonic inspection, force history and residual stiffness studies [7, 8]. It is observed that the sub-critical impacts of 3 J, before and after the 15 J impact, presents a sinusoidal shape corresponding to the elastic regime, the differences between them are in the maximum force reached and the contact time during the impact; both related with the change of stiffness due to the damage induced by the supercritical impact (15 J). This change of contact time has been used to measure the residual stiffness of the plate [4, 6]. The force history corresponding to the supercritical impact of 15 J presents a different trend, a linear increase of force (Point A) until a sudden drop (Point B); then the trend of force becomes more erratic reaching the maximum force (Point C). From this point the force decreases (Point D) to zero. Images of the back of the laminate obtained by means of the high speed video camera are shown for these different instants, note that the laminated was painted in white for an easier visualization. The linear increase (frame A) ends with the appearance of fiber damage at the back face (frame B). The fiber breakage increases until the maximum peak force (frame C) and it remains constant during the decrease of force (frame D). As expected, the fiber damage during the impact develops perpendicularly to the smaller specimen side, because this boundary condition induce higher stress in this direction.

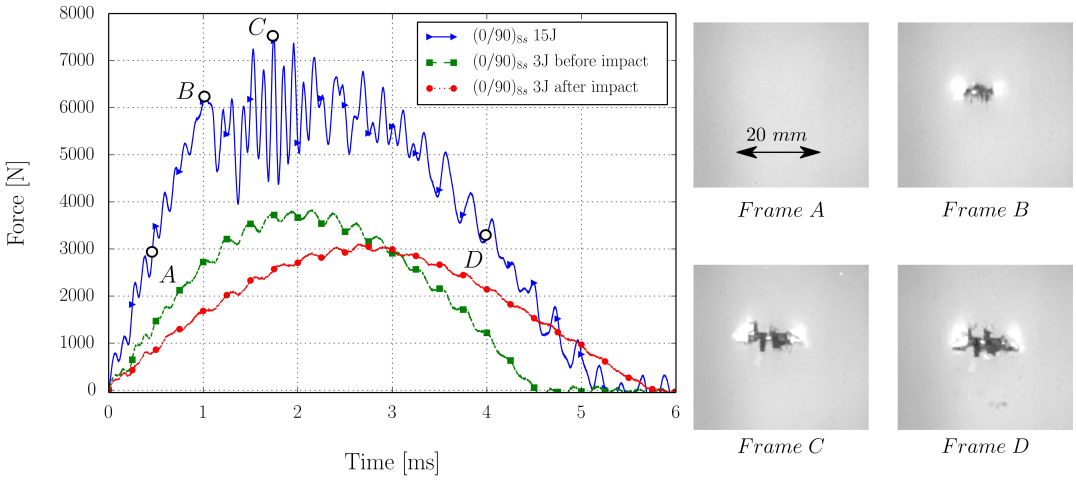

Figure 1. Force history and images from an impact of 15 J in a $(0/90)_{8s}$ laminate.

The following section uses these histories and its primitives (acceleration, velocity and displacement) to study the influence of the selected parameter (thickness, ply sequence and ply clustering).

3.1. Influence of thickness

Experimental low velocity impacts were performed in specimens with 2.3, 3.5 and 4.6 [mm] of thickness (Specimens A, B and C from Table 1) as this parameter has been shown as a driver parameter in the laminate behavior. Increasing the number of plies, raises the stiffness and the ability of withstand impacts. In fact the sub-critical impact of 3 J was delimited by the thinner laminate (2.3 mm), as it is the one which

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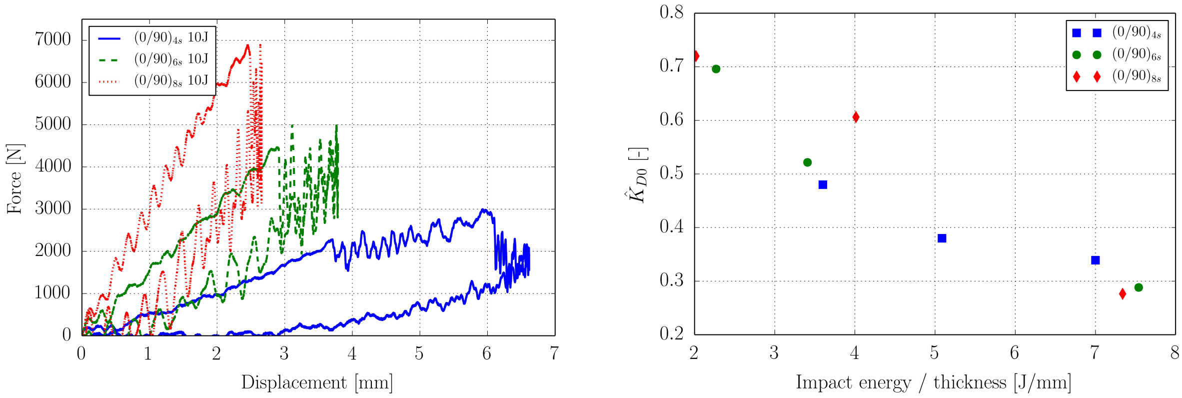
can bear less force before damage. Fig. 2(a) shows the force as a function of the striker displacement for an impact of 10 J for the three laminate thickness. The differences in stiffness of the laminates are remarkably, double the number of plies (between 8 to 16 plies) produces an increment of stiffness of around 5.5 times ($\sim 550\ N/mm$ to $\sim 3000\ N/mm$). The force that the laminates withstand increases 2 times between laminates of 8 and 16 plies; moreover the compliance of the laminates increases raising the maximum displacement reached (Fig. 2(a)). Finally, the residual stiffness ($\hat{K}_{D0}$) as a function of the ratio between the impact energy and the thickness, shows that the loss of stiffness due to the impact is influenced by the number of plies of the laminate [9].



(a) Force versus displacement of impacts at 10 J

(b) Residual stiffness versus impact energy

Figure 2. Comparison of laminate thickness.

3.2. Influence of ply sequence

Regarding the influence of ply sequence in the response of laminates subjected to low velocity impacts, Fig. 3(a) shows force as a function of the displacement of the striker for two different ply sequence laminates $(0/90)_{8s}$ and $(\pm 45)_{8s}$ subjected to impact at around 10 J (9.28 J and 8.8 J respectively). Fig. 3(a) shows differences in the stiffness of the laminates, nevertheless in accordance with the effective plate stiffness proposed by the classical plate theory and Olsson et al. [10]:

$$D^{\star} = \sqrt{D_{11} D_{22} (A + 1)/2} \tag{1}$$

(where $A = (D_{12} + 2D_{66})/\sqrt{D_{11} D_{22}}$) both laminates should have the same value of $D^{\star} = 137.5\ GPa$; the differences are due to the combination of ply orientation and the non-symmetric boundary condition of the test.

Both ply sequence reach similar values of maximum force and maximum displacement; the maximum force for the $(\pm 45)_{8s}$ is slightly lower than the reached by the $(0/90)_{8s}$ laminate at the same impact energy. Whereas the amount of displacement after the sudden drop (point A and B in Fig. 3(a)) is bigger for the $(\pm 45)_{8s}$. No remarkable differences are appreciated in the maximum force for different impact energies, neither in the values nor the trend. Similar conclusion can be obtained from the residual stiffness as a function of the impact energy Fig. 3(b). Instead differences could be found in the amount of fiber breakage. Fig. 4(b) and 4(a) shows the extension of damage at back face for both ply sequence impacted at around 35 J, the $(0/90)_{8s}$ shows around a 26% more of fiber breakage length than in the other ply sequence. Although the displacement suffered after the start of fiber breakage in $(0/90)_{8s}$ is smaller than in the other laminate sequence the higher stress distribution due to fiber orientation and BC's could produce higher amount of breakage.

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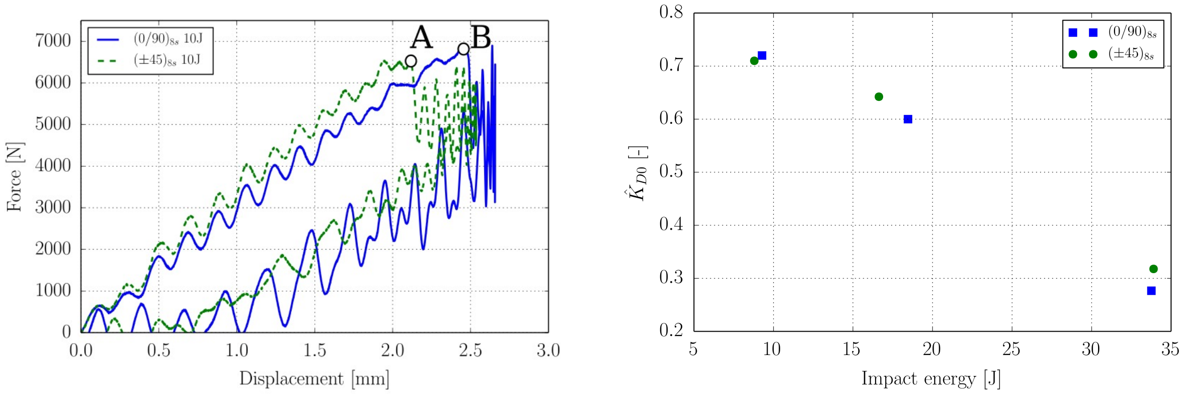
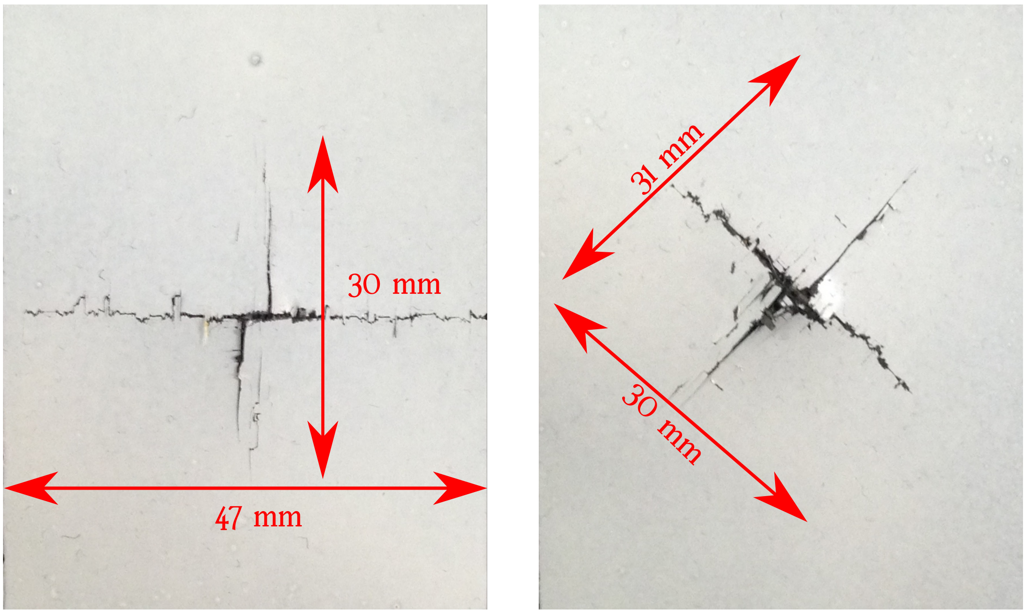


(a) Force versus displacement of impacts at 10 J

(b) Residual stiffness versus impact energy

Figure 3. Comparison of ply sequence for $(0/90)_{8s}$ and $(\pm45)_{8s}$ laminates.



(a) $(0/90)_{8s}$

(b) $(\pm45)_{8s}$

Figure 4. Comparison of damage at back face in $(0/90)_{8s}$ and $(\pm45)_{8s}$ laminates impacted at 40 J.

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3.3. Influence of ply clustering

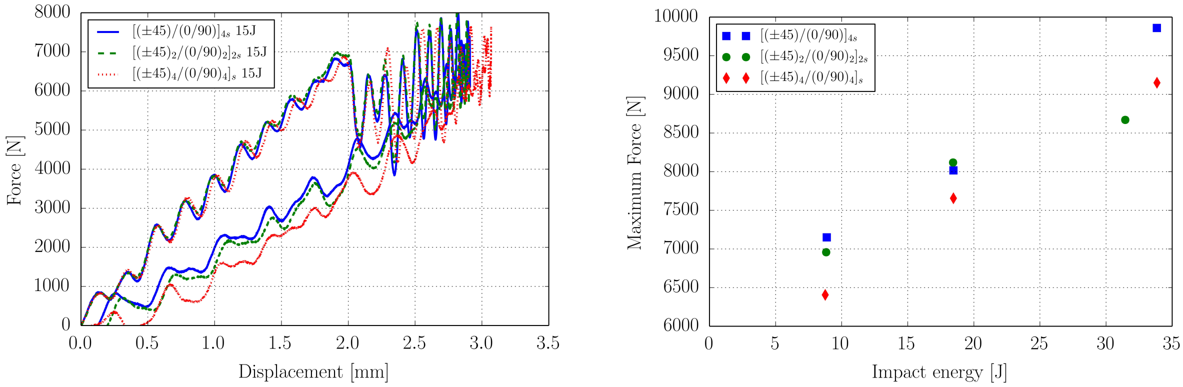
Finally a similar study of the low velocity impacts has been done for the ply clustering (laminates E, F and G from Table 1). Although the laminates present different values of $D^\star$ [10], the differences are below 1% (140.44 GPa – 139.008 GPa see on Table 2) and the force histories confirm this low difference (Fig. 5(a)). In these cases the BC's affects per equal in the laminate due to all plates have the same number of plies oriented in each direction (clustered or not).

The maximum force shows differences between the ply clustering (Fig. 5(a)), the laminate with less effective plate stiffness $D^\star$ reach a lower value of maximum force than the other. The residual stiffness ($\hat{K}_{D0}$) plate without ply clustering ($[(\pm45)/(0/90)]_{4s}$) decreases less than in the other laminates as the impact energy increases. As the plate contains more interfaces between plies with different orientation

Table 2. Effective plate stiffness of the different laminates.

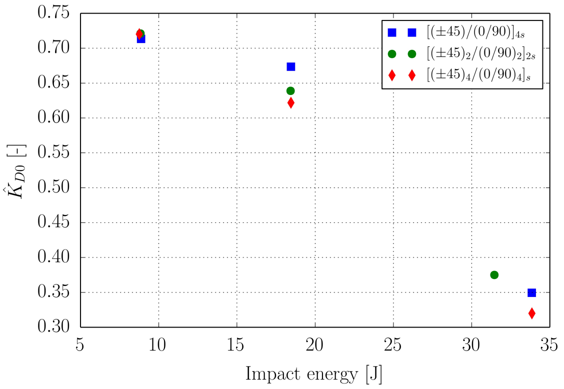
Configuration	Ply sequence	$D^\star$
E	$[(\pm45)/(0/90)]_{4s}$	140.44 GPa
F	$[(\pm45)_2/(0/90)_2]_{2s}$	140.16 GPa
G	$[(\pm45)_4/(0/90)_4]_s$	139.08 GPa

it is capable to absorb more energy in delamination with lower spread in the area, thus loosing less out-of-plane stiffness.



(a) Force versus displacement of impacts at 15 J

(b) Maximum force versus impact energy



(c) Residual stiffness versus impact energy

Figure 5. Comparison of ply clustering for $[(\pm45)/(0/90)]_{4s}$, $[(\pm45)_2/(0/90)_2]_{2s}$ and $[(\pm45)_4/(0/90)_4]_s$ laminates.

4. Conclusion

The influences of ply thickness, ply sequence and ply clustering in the low velocity impact respond has been studied. Regarding the influence of these parameters:

- The ply thickness is a driven parameter in the force that laminates withstand and in the maximum deflection. The residual stiffness $\hat{K}_{D0}$ is linear with the ratio between the impact energy and the thickness.

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- Regarding the ply sequence laminates with $(0/90)_{8s}$ and $(\pm 45)_{8s}$ are compared. As expected, the ply sequence controls the damage orientation. In addition, the amount of fiber breakages observed change with the ply sequence.
- The ply clustering of the laminates influence the maximum force and the residual stiffness. The effective plate stiffness $D^{\star}$ controls the maximum withstand force and the residual stiffness $\hat{K}_{D0}$ is influenced by the number of interfaces.

Acknowledgments

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